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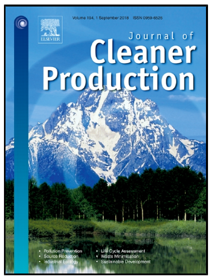

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Title Page

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Investigating the energy transition to a coal-free residential sector in Kazakhstan using a regionally disaggregated energy systems model

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Highlights

- Improved modeling framework for decarbonizing residential energy is presented
- Effects of a coal ban and clean technology subsidies were investigated
- Results point to networked gas for households and district heating for flats

Abstract

Problems with unsustainable use of energy by households and lack of access to energy infrastructure require effective actions from the policy makers. Energy system models can usefully analyse future residential sector energy pathways "within" the full energy system. However, few energy system models have been developed with disaggregated sub-national regional detail, building type and urban/rural divisions. This paper addresses this key gap. Disaggregating the residential sector by building categories allows improved representation of the range of energy transition options across building categories. We incorporated a novel detailed building stock module into a 16-region TIMES energy systems model for Kazakhstan, using statistical data on the housing stock and building energy audit reports. We then explore the introduction of a coal ban and use scenario analysis to identify the most cost-effective heating technologies for the different regions and different building types. Implications of the residential sector policies to the supply side energy infrastructure were also quantified.

The energy transition (from solid fuels to cleaner alternatives) is rarely achievable without Government intervention, therefore scenarios with ban on coal use and clean energy technology subsidies (micro-CHP, heat pumps and solar space heaters) have been investigated in this study. The results indicate that in rural areas networked gas (for detached households) and district heating (for flats) are more economically viable substitutes to coal, even with subsidies offered for clean technologies. In the scenario with the constraint on gas network expansion and clean technology subsidies, there is a wide utilization of heat pumps in detached rural houses. Subsidies for retrofit measures are effective with wide utilisation, especially in the areas affected by the coal ban, with up to 76% reduction of the useful energy demand. The total amount of allocated subsidies for clean technologies amounted for up to 32% and 8% of the current state social and health care expenditures. A coal ban in the residential sector is estimated to achieve emissions reductions for $PM_{2.5}$ and CO of 92% and 95%, respectively (compared to the base year level), even accounting for emissions from the supply side (power plants, heat plants).

Keywords: housing stock; heat; energy system model; coal; Kazakhstan

1. Introduction

1.1 Background

Globally, the number of persons using wood, coal, charcoal or animal waste for cooking and heating is roughly 3 billion (UN, 2018) and it has remained stable during 1980-2010 (Bonjour et al., 2013). Ensuring access to affordable, reliable, sustainable and modern energy for all is one of the 17 Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development (UN, 2018). In the developing countries context, residential emissions from space heating and cooking with solid fuels remain to be an important and generally unrecognized source of ambient air pollution (Liu et al., 2016). Concerns with unsustainable use of energy, lack of access to modern fuels and energy poverty challenges, all require effective actions from policy makers.

The energy transition is rarely if ever achievable without coordinated support and regulation from the Government. In some countries, a residential coal ban has been demonstrated to be an effective measure (Dockery et al., 2013), but it needs to be carefully applied in the regions with no other alternative options coupled with high poverty rates. In many countries, there are support programs for building scale renewable energy installations for space heating and for retrofitting measures (IEA, 2017). The design of successful policy intervention needs quantitative assessment of possible impacts and prioritizing regions, technology types, as well as identifying optimal subsidy levels. One of the goals of this paper is to provide necessary and useful information to inform the policy making process to address this important challenge.

1.2 Kazakhstan context

Poor building insulation coupled with low access to clean fuels in some of its regions resulted in significant challenges associated with "energy poverty" in Kazakhstani households (Kerimray et al., 2017a). Households that are not able to adequately heat their homes at an affordable cost or/and adequately access clean fuels are defined as energy poor. Many rural households still use solid fuels for heating purposes (Atakhanova and Howie, 2013). Coal is mostly burned domestically in open fires with low efficiency (Stoyak et al., 2017) and it results in significant adverse impacts on outdoor and indoor air quality, which in turn leads to severe health impacts (WHO, 2004). In Kazakhstan there are currently no policy interventions to support the energy transition and buildings retrofit in the residential sector. There is also an absence of analysis and, to our knowledge, this is the first energy modelling scenario analysis study on Kazakhstan's residential sector in the literature.

1.3 Approaches for representing residential sector in the energy system models and its application

Amongst the multitude of options for the energy transition (e.g. renewable energy, biomass, heat pumps, etc.) and for energy demand reduction (retrofit options), the optimal strategy depends on the building type, use, age, geographical location and other given conditions, as well as on the goals of decision makers (Wu et al., 2017). Energy systems modelling has an advantage in exploring these options as it simultaneously optimizes the supply and demand of energy, taking into account the availability of resources (e.g. gas and renewable energy among others) and the role of infrastructure (e.g. power plants and gas network among others) necessary for energy transition in the residential heating sector. Thus, energy system models are capable of analysing the residential sector "within" the full energy system, which allows us to understand the impact of sectors specific policies and measures for the system (e.g. emissions) or vice-versa (extending gas network for the residential sector).

An important limitation in the application to date of energy system models for residential sector analyses is that in most cases, the projections of energy services demand for residential buildings is often approached in a simplified way; for example, based on the simplified relations between energy consumption and income or GDP per capita (Gouveia et al., 2012). This paper addresses this limitation by using projection of physical units (surface area of the dwelling stock) as a driver for the heating end-use demand, since the heating need is a function of the surface area (among with other parameters). Similar approach was used for models of China (Shi et al., 2016) and Portugal (Gouveia et al., 2012).

There can be vast differences between regions and building types in the access to fuels, the energy infrastructure and the heating demand, as in the case of Kazakhstan (Kerimray et al, 2017a). This makes Kazakhstan a good case study to test improved methods in disaggregation. Fehrenbach et al. (2014) concluded that the aggregation of demand types and the granularity of the geographical representation might lead to inaccurate evaluation of the heating demand. An additional level of disaggregation of the residential sector can be particularly important for cold climate countries with a substantial proportion of total energy use (Dodds, 2014). There are very few energy system models with both detailed buildings sector and regional detail and these include models for Canada with 4 building types (Vaillancourt et al, 2014), for China with urban/rural divide (Shi et al, 2016), for Italy with 6 building types (De Miglio et al, 2015) and for Denmark with 4 building types (Petrović and Karlsson, 2016). To our knowledge, the particular challenges of households in developing countries, including insufficient level of thermal comfort, access to infrastructure (energy poverty) which is highly heterogenous, has been rarely analysed with the energy system models.

Gouveia et al. (2012) studied the impact of varying thermal comfort values and concluded that increased attention should be given to thermal comfort expectation due to the high impact of this parameter on the resulting energy services demand. Due to the absence of the surveyed data on thermal comfort and occupancy rate, in this study it was not possible to conduct detailed analysis with varying thermal comfort level. Nevertheless, “reduced demand” was quantified (by assessment of heating and dwelling stock) and introduced to the energy system model.

Bhattacharyya and Timilsina (2010) reviewed the suitability of energy system models for developing countries and stressed the need for better characterization of urban/rural division and spatial distribution in the models in order to properly account for the heterogeneous challenges present in developing countries. Important challenges of employing energy system models for developing countries include the need for high level disaggregated data as well as high level of skills needed for the model development (Bhattacharyya and Timilsina, 2010). The first objective of this study is to present an improved approach for representing and analyzing the challenges (spatial, urban/rural and buildings types differences, accounting for “reduced” demand) of developing countries within energy systems modelling. This approach centers on representing the dwelling stock as a driver for the end-use heating demand in the energy system model. The second objective is to provide robust, knowledge-based information to underpin policy decisions on pathways towards a coal-free residential sector in Kazakhstan by employing advanced modeling techniques. This includes presenting a detailed analysis of the retrofit measures of dwelling stock, as well as assessment of the heating needs.

2. Methodology

2.1 Energy system models

This study will make use of the TIMES (The Integrate Markal-EFOM System) model generator, which is a widely-applied partial equilibrium, bottom-up, dynamic, linear programming optimization model. According to reviews of energy system models (Bhattacharyya and Timilsina, 2010), TIMES/MARKAL is one of today’s best-known energy system modeling platforms. The advantages of TIMES/MARKAL models over other energy system models include its extensive technology coverage, user defined level of disaggregation, and capability to analyze both price and non-price induced policies. The long-term energy system model defines the investments, operation modes of the energy system, production and consumption of various goods (fuel, materials, energy services) and their prices in such a way that production is exactly equal to consumption. The main advantage of such models is that these models provide an exhaustive description of possible scenarios for development of the energy system by considering intertemporal, interregional and intersectoral relations.

The characteristics of TIMES/MARKAL models have been explained in its documentation by Loulou et al. (2016). These are technology-oriented models that require information on technical and economic characteristics of various technologies within the whole energy supply and demand chain. User provides information on the existing stocks of energy technologies in all sectors, and the characteristics of available future technologies, as well as present and future sources of primary energy supply and their potentials (Loulou et al., 2016). While computing the equilibrium, TIMES model configures the energy system over a time horizon and a set of regions, in such a way as to minimize the net total cost (or equivalently maximize the net total surplus) of the system, while satisfying several constraints (e.g. technical, environmental, capacity).

TIMES model computes for each region a total net present value (Eq.1) and these regional discounted costs are then aggregated into a single total cost, which constitutes the objective function to be minimized by the model in its equilibrium computation based on linear programming (Loulou et al, 2016).

$$NPV = \Sigma_{r=1}^{R} \Sigma_{y \epsilon YEARS} (1 + d_{r,y})^{REFYR - y} \times ANNCOST(r,y) \quad (1)$$

Where:

NPV - is the net present value of the total cost for all regions (the TIMES objective function);

ANNCOST(r,y) - is the total annual cost in region r and year y;

$d_{r,y}$ - is the general discount rate;

REFYR is the reference year for discounting;

YEARS is the set of years for which there are costs;

R is the set of regions in the area of study.

2.2 The TIMES-Kazakhstan multi-regional model

The TIMES-Kazakhstan multi-regional model represents region by region all the steps of the energy chain from supply to end-use: from the extraction of primary resources to their supply to primary energy markets, from the transformation of primary energy carriers to their transmission and distribution to the final energy-use sectors, from use of final energy commodities to satisfying the end users demand for energy services (Suleimenov et al., 2016). The model for Kazakhstan is calibrated to the year 2011 (base year) with the data provided by the regional energy balances (Kazmaganbetova et al., 2016). Due to inconsistencies in the Energy Balances published by the Committee of Statistics of the Republic of Kazakhstan, improved versions of the Energy Balances for Kazakhstan were compiled and cross-checked with additional data (Kerimray et al., 2017b), as described in the Appendix A. Inconsistencies include double counting, inappropriate allocation of fuels to sectors, allocation of consumed energy to 'not-specified'/'other'/'statistical differences' (Kerimray et al., 2017b).

The multiregional model of Kazakhstan is based on sixteen (16) structurally interconnected regional sub-models, which are allowed to trade energy forms through the existing and new "capital intensive" infrastructures (pipelines for crude oil and natural gas), through electrical grids and via land transport (oil products and coal) on the basis of synergic needs of the sub-national systems. Capacities of the existing infrastructures are used to describe the maximum level of "tradable" energy between pairs of regions; new investments are allowed to enable future extra exchanges of resources driven by exogenous plans (e.g. extension of gas network) and/or by endogenous synergies (cost-effective decisions).

2.3 Residential sector. From data collection to representation in the model

2.3.1 Residential sector analysis

Residential sector is the third-leading energy consuming sector in Kazakhstan after the energy industries and manufacturing industry sectors (Kerimray et al., 2016). As estimated by the Government, the annual energy consumption for heating in the residential buildings was 270 kWh/m^2, which is more than two times higher than average European levels (100-120 kWh/m^2) (Government of the Republic of Kazakhstan, 2013). Cold winters, dilapidation of housing stock, losses of heat through the building envelope elements and inefficient appliances are among possible reasons of high energy consumption in the sector (Kerimray et al., 2016).

There is a dilapidation of the dwelling stock as most of the building stock in Kazakhstan were constructed before 1985 (59%), 29% between 1985 and 2005, and only 12% after 2005 (Kerimray et al., 2017a). This is explained by massive construction of "standard" modular buildings in the Soviet Union during the period from 1959 to 1985.

The surface area of building categories is different from region to region (Fig.1). In colder climate regions, share of flats in the total dwelling stock is predominant (70%), while in the warmer regions detached houses are predominant (58%).

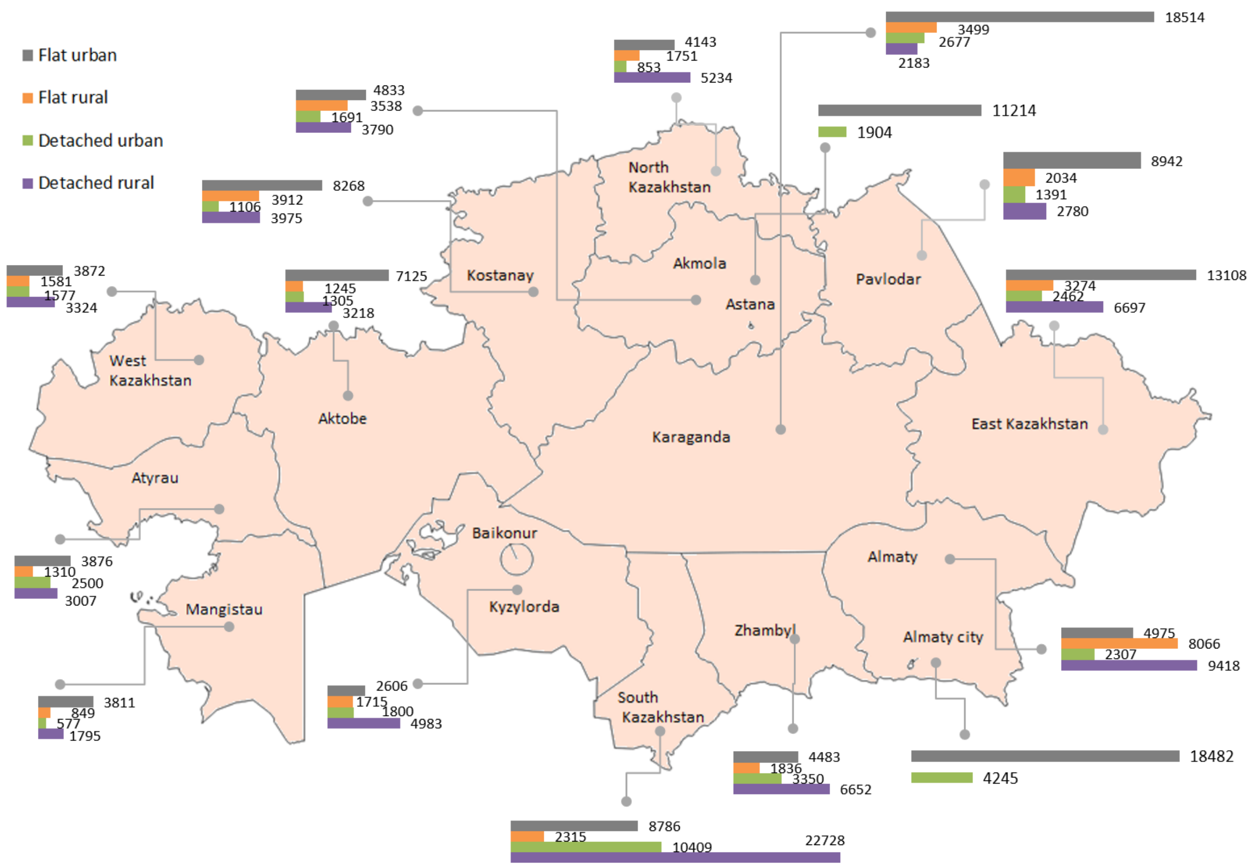


Figure 1. Living surface area of residential dwelling stock in Kazakhstan in 2011 (base year), thousand m^2 (Committee of Statistics of the Republic of Kazakhstan, 2016)

The average heat transfer coefficient (U-values) of building envelope elements in Kazakhstan for wall, ceiling, floor and windows are presented in Table 1 (adapted using data from the building energy audit reports, Kerimray et al., 2016). Buildings energy audit reports (586 in total) conducted by accredited energy auditing companies across all regions of Kazakhstan were collected to estimate the heat transfer coefficients of building elements (walls, windows, floors, roofs and doors) by building types. These values are rather high, meaning that there are additional heat losses through the building envelope elements, relative to other regions, e.g. Finland. The heat transfer coefficient of Finland's buildings is lower compared to Kazakhstan's buildings, by up to 4.7 times for walls, 3.4 times for ceilings, 2.6 times for floor and 1.28 times for windows.

Table 1. Average U-values by building age in Kazakhstan and Finland

U values, W/m^2K	Walls	Ceilings	Floors	Windows	Doors
Kazakhstan					
before 1969	1.01	0.70	0.64	2.32	3.55
1970-1979	1.11	0.72	0.72	2.24	3.62
1980-1989	1.19	0.72	0.60	2.24	3.21
1990-1999	1.13	0.66	0.59	2.20	3.69
2000-2014	1.22	0.62	0.72	1.92	1.66
Finland					
before 1969	0.56	0.38	0.45	2.2	N/A
1970-1979	0.41	0.29	0.37	2.05	N/A
1980-1989	0.29	0.23	0.33	1.75	N/A
1990-1999	0.28	0.22	0.32	1.75	N/A
2000-2014	0.26	0.18	0.28	1.5	N/A

It can be also seen from the Table 1 that relatively new buildings do not necessary have improved heat transfer characteristics. This can be due to the fact that the legislation on energy efficiency have been introduced relatively recently (in 2012).

2.3.2 Steps for constructing building stock module

Disaggregating the residential sector by building categories allows improved representation of the range of energy transition options across building categories. Residential buildings were disaggregated to 4 types: urban detached, rural detached, urban flats and rural flats. This type of disaggregation was chosen due to varying level of heating demand by building categories and, the access to energy infrastructures, which can have an impact on the selection of the technology selection options.

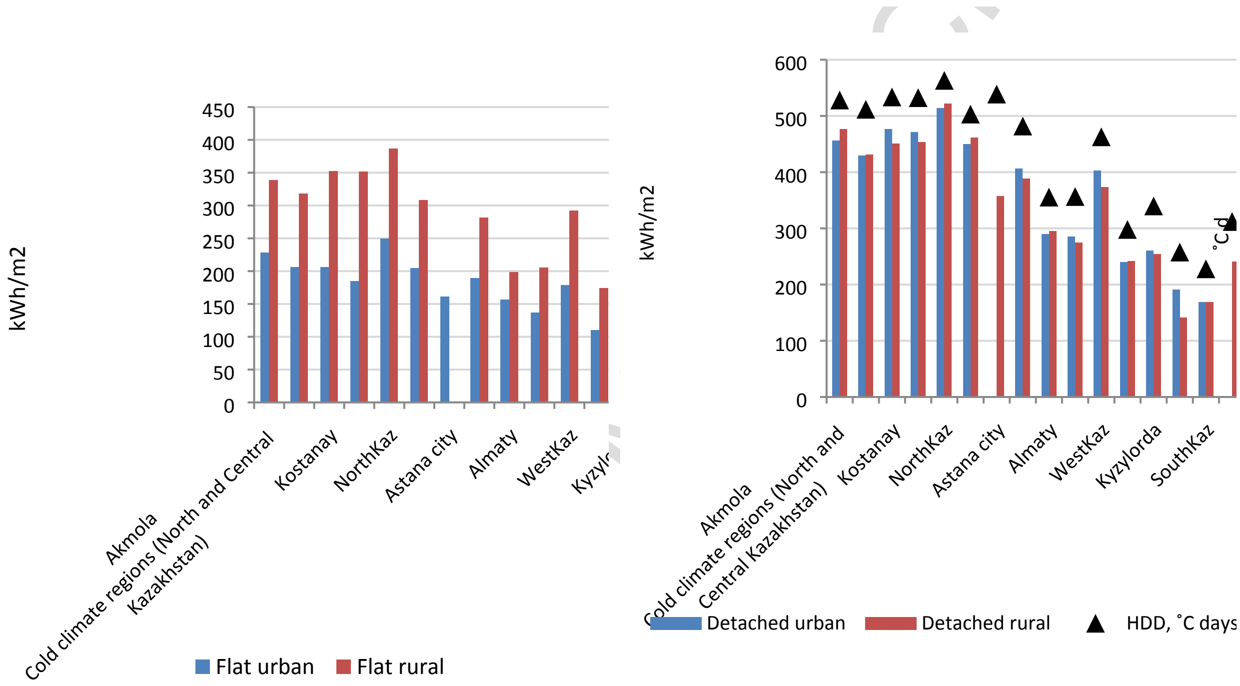
Due to the high heat losses through building envelope elements, building retrofit measures can play an important role in achieving the energy transition in the residential sector. Energy savings and costs of building retrofit measures vary depending on the building type and climatic condition of the region, therefore representation of the building categories improves understanding the role of the building retrofit measures by building type.

The building stock module for the TIMES model was developed using the following steps::

1. Collection of data on surface area of residential buildings by: urban/rural, detached/flat, 16 regions, wall material and building age (Figs. 1, 2); estimation of average geometries of dwellings by building type based on statistics of surface area and number of constructions by building type published by the Committee of Statistics of the Republic of Kazakhstan (2016).

2. Collection and analysis of buildings energy audit reports (Kerimray et al., 2016), including:
    a. estimation of average heat transfer coefficients of building elements by building type.
    b. estimation of costs of retrofitting measures.
    c. heat transfer coefficients of refurbished building elements.
3. Calculation of the theoretical heating need by building type and by region based on ISO 13790 "Thermal performance of buildings and building components". Heating-Degree-Days and heating season duration by regions of Kazakhstan was obtained from the Building Code "Energy consumption and thermal protection of buildings" (Construction Norms of the Republic of Kazakhstan 2.04-21-2004).
4. Assessment of energy saving from retrofitting measures by building type estimated as a difference between the theoretical heating need and heating need after retrofit measure.
5. Comparison of theoretical heating consumption in the base year (2011) with energy statistics on actual energy consumption, assuming occupancy rate and calibrating the model.

The methodology for the assessment of heating needs by building type is presented in the Appendix B. Energy need for heating is heat to be delivered to, or extracted from, a conditioned space to maintain the intended temperature conditions during a given period of time. The resulting estimated heating need is presented in Fig. 2. There are significant variations in heating needs from region to region of Kazakhstan which are determined by differences in climatic conditions (heating-degree-days) and between flats and detached houses as heating need is a function of surface area to volume (S/V) ratio. The highest heating need occurs in detached rural houses in Northern Kazakhstan which require 450-500 kWh/m^2 per year. Large variations of heating needs between climatic zones of Kazakhstan and type of buildings construction prove that quantitative assessments, future scenarios and policy actions for technology mix should account for these uneven initial conditions.



(a) (b)

Fig. 2 Estimated heating need a) flat (left axis); and b) detached buildings (left axis) and Heating-Degree-Days (right axis)

The retrofitting measures that are represented in the model, with corresponding saving potentials and costs are summarized in Table 3. The data were obtained from the Reference values for Kazakhstan ENSI EAB (software for building energy auditors) and building energy audit reports.

Table 3. Building envelope retrofit measures (adapted from Kerimray et al, 2016)

Measure	Building envelope				
	New windows	Wall insulation	Ceiling	Floor	Door
Short description	Replacement of old windows with new plastic	50 mm insulation made of polystyrene or mineral wool with outer layer of plaster	150 mm cellulose fiber insulation	Insulation made of polystyrene or mineral wool with outer layer of plaster	Insulated metal door with a door closer
U value, W/m²K	1.60	0.65	0.17	0.35	1.66
Total cost, USD/m² (per area of insulated element)	153	19	10	3	420

2.3.3 "Reduced" demand and occupancy rate

Actual heating need is a function of households' occupant behavior and equipment utilization. A difference exists between theoretical and actual heating needs as households are not constantly occupied and thereby, not always heated. Even if it is occupied, not all the household area is heated to the same indoor temperature (Gouveia et al., 2012). Due to relatively high energy costs and low incomes, householders may not heat their homes to the sufficient comfort level, resulting in a lower demand due to energy poverty.

In the model, heating need is based on estimated theoretical value (Fig. 2), while heating consumption was calibrated in accordance with the energy balances. Thus, the difference between estimated and actual heating need (corrected with stock component) was assumed to be “reduced demand” that includes the lower demand due to energy poverty and due to the other factors mentioned. It was assumed that in all scenarios the entire “reduced” demand is satisfied by 2030. The stock component (occupancy rate) was assumed to be 81% (national average) in the absence of studies on occupancy and indoor temperature. The “reduced” demand was estimated as a difference between theoretical and actual heating need, corrected with occupancy rate assumption. The resulting “reduced” demand (corrected with 81% occupancy rate) was estimated to be 24906 TJ or 13% of total heating need (based on actual data) in the base year 2011. The details on “reduced demand” and “occupancy” rate values are presented in the Appendix C.

2.3.4 Model representation

The demand for residential heating is represented in the building stock module of the TIMES-Kazakhstan multi-regional model by heated surface area divided in 4*3 types: flat/detached, urban/rural, and new/existing/passive (Fig. 3). New buildings and passive houses have different heating needs compared to existing dwellings.

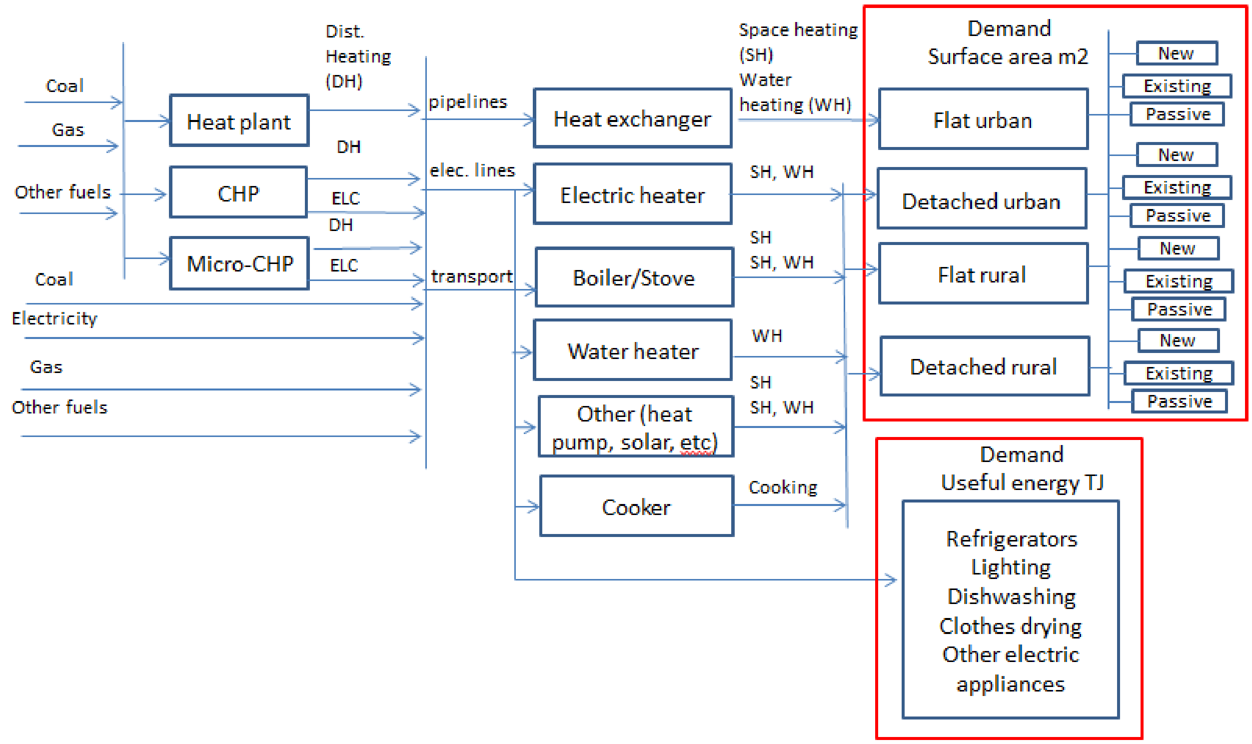


Fig. 3 Residential sector structure in revised version of the TIMES-Kazakhstan multi-regional model

According to the Law "On energy saving and energy efficiency" adopted in 2012, all new buildings must not be less than Class C (normal). Thus, at a minimum, the heating need should be less than the "normal" heating (class C) need values determined by construction norms of the Republic of Kazakhstan 2.04-21-2004. For all scenarios in the model, it was assumed that new buildings do not have less than Class C heating needs.

The total amount of heated area served is a driver of the demand for space heating, water heating and cooking. The total annual increase in heated area is calibrated according to statistical data for 2015 and total annual increase corresponds with the parameters of the State Program "Affordable

Housing - 2020". More details on approach for estimation of projection of surface area is presented in Appendix D.

Sources of information for the new technology database are presented in Appendix E. Assumptions on the costs and routes for gas pipeline infrastructure are presented in the Appendix F.

The emission coefficients for air pollutants (NO_x, CO, SO_x, $PM_{2.5}$) were obtained from EMEP/EEA air pollutant emission inventory guidebook (EMEP/EEA, 2016). GHG emission factors were obtained from the Kazakhstan's inventory submission to the UNFCCC.

2.4 Energy transition scenarios

Scenarios analyzed in this study are presented in Table 5.

Table 5. Definition of energy transition scenarios to be explored.

Scenario name	**Definition**
Reference	No constraints on the use of coal use, no subsidies for cleaner technologies, reference trend of energy efficiency improvement and fuels substitution.
Coal-ban	Phase-out of coal use in the residential sector (40% reduction of coal use by 2020 and 100% reduction by 2030 compared to the level of 2011).
Coal-ban-subs	- Subsidies on the capacity for cleaner alternatives: micro-CHP (biogas, biomass, natural gas), heat pumps and solar space heaters in the amount of 70% of the investment cost.

	- Subsidies for the retrofit measures (50% of the cost): wall, roof, floor, loft, door, windows.
Coal-ban-subs-no-gas	The same as in “BAN+subsidies” scenario, but construction of new network gas pipeline to the northern and central Kazakhstan is not allowed.

Reference scenario. Least Cost Solution or "Reference” scenario represents the system subject to optimal policy design. Nature of the optimization models implies that all scenarios represent least cost solution, with the differences in assumptions and constraints additionally imposed to the particular scenario.

Coal-ban. Bans on coal sales is has been widely applied in many developed countries. Coal phase out or optimal coal-free configuration residential sector was assumed to be the core energy transition scenario (coal-ban) for which additional assumptions/constraints were imposed to test alternative pathways.

Coal-ban-subs. Despite the availability of mature clean technologies for space heating, they may require targeted financial support from the governments due to their high costs and/or low levels of income of households (Kerimray et al, 2017c). The reduced (subsidized) cost of the clean technologies in the model may have substantial impact on the resulting optimal technology mix. In this regard, the scenarios with subsidized (Coal-ban-subs) and with unsubsidized clean technologies (Coal-ban) were compared with the aim to compare the impact and efficiency of the subsidization.

Technology penetration on the different level of subsidies for cleaner technologies was tested: from 30% to 100% of the investment cost. Subsidy levels of up to 50% lead to a maximum of only a 1-2% of penetration of subsidized technologies in satisfying the useful energy demand for heating (without constraining network gas). Higher subsidy levels of 60%, 70%, 80%, 90% led to up to 5%, 8%, 12%, 19% penetration of subsidized technologies respectively (depending on the building type, without constraining network gas). A 100% subsidy lead to up to 80% of penetration of subsidized technologies even without constraining network gas. In this study, 70% of subsidization level has been tested. As technology penetration analysis demonstrated, 70% level of subsidy can be considered by policy makers as appropriate to support clean technologies.

Coal-ban-subs-no-gas. Construction of gas pipeline to the non-gasified regions can be economically viable solution in the coal-free residential sector pathway, however the construction of gas pipelines is capital intensive and can be postponed or cancelled, scenarios with and without constraints on gas pipeline construction were also investigated and compared.

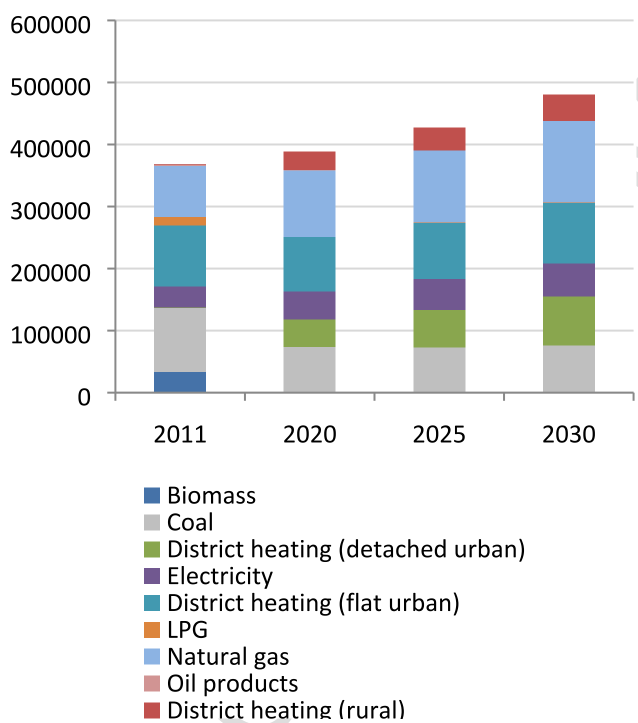
3 Model results

3.3 Fuel and technology selection

Coal remains to be the main fuel for heating in rural detached houses in the regions without gas availability in the absence of policy interventions (Reference) (Fig. 4). Total coal consumption however, reduces by 27% in 2030 compared to the base year level in Reference scenario. This is because the model finds least cost solution and hence in some regions with a gas network, particularly in the southern parts of the country, the model points to a switch from coal to gas in , even without any interventions. This occurs as a result of long distances from coal mines, relatively high coal price (in gas regions), as well as lower combustion efficiency of coal stove compared to gas boilers.

In the scenario where coal is banned, it is mainly substituted with natural gas, district heating and electricity (in areas where no gas pipeline is available) (Fig.4). In addition, higher efficient technologies and retrofit measures are utilized, which results in the reduction of residential energy consumption by 9% in coal-ban and 15% in coal-ban-subs scenario in 2030 compared to the Reference scenario.

(a)



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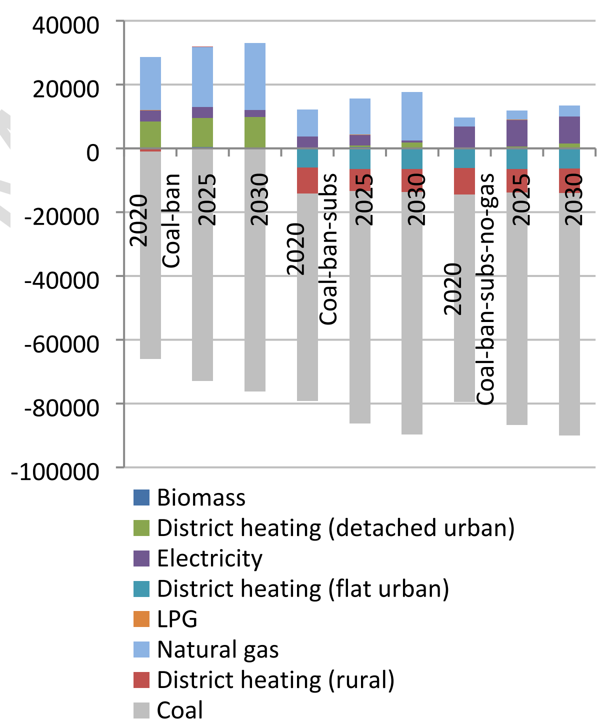


Fig. 4 – a) Energy consumption in the residential by 2030 in Reference scenario, TJ b) Difference in energy consumption between alternative and Reference scenarios (TJ)

Regions with high coal use (including some regions in the South) have the highest savings from retrofit measures when coal is banned and subsidies are offered (Fig.5). Absence of gas pipeline (Coal-ban-subs-no-gas) does not bring additional energy demand savings from retrofit measures compared to the case when the gas pipeline is allowed (Coal-ban-subs). This demonstrates that retrofit measures potential are fully utilized, indicating their cost-effectiveness even with gas network availability (in the subsidized case).

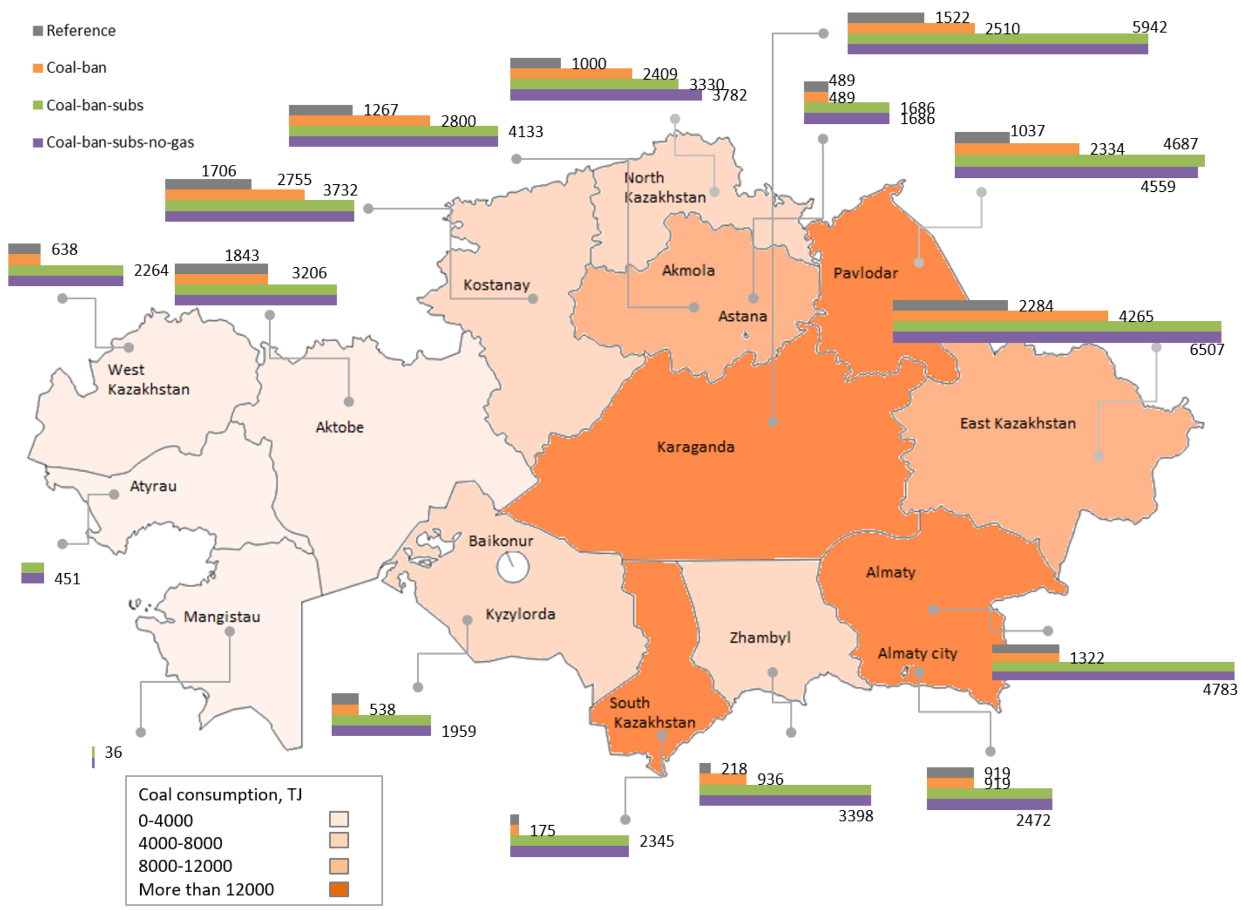


Fig. 5 – Regional results - Useful energy reduced by retrofit measures in 2030, TJ; Residential coal consumption by regions of Kazakhstan in the base year, TJ[1]

[1] Kostanay region is the only region located in North Kazakhstan with access to networked gas, which is supplied from Russia via SWAP agreements

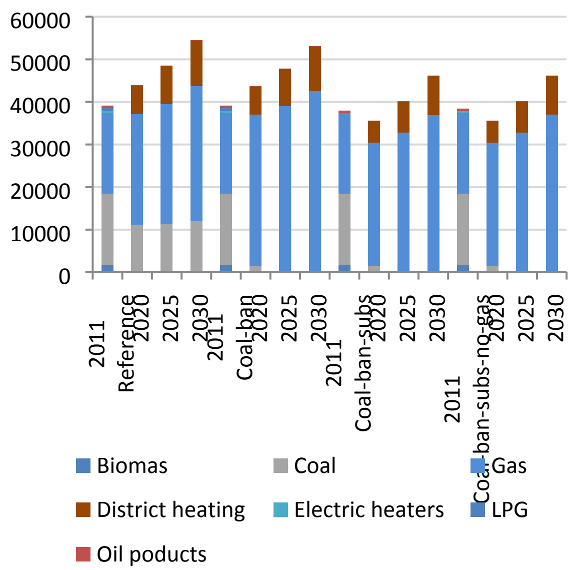
Figures 6-8 compares useful energy for space heating by technology selection and by scenario, by building types and by two regional aggregations: with and without gas network availability. The following conclusions can be made by scenarios:

- *Reference scenario* (compared to the base year). This scenario has a minor effect on technology mix in the urban flats and detached rural houses, however considerable impact was observed in detached urban and flat rural houses. District heating, which not utilized in the base year, start to dominate technology mix in the detached urban and flat rural houses by 2030.
- *Coal ban* (compared to Reference scenario) has an impact on rural areas in both regions (with and without gas network) due to the fact that in the base year rural areas were heavily dependent on coal in the both regions (43% share of useful demand for heating in the regions with gas and 83% in the regions without gas).
    - *Detached rural houses*. In the regions with gas network, network gas dominate (80%) in all alternative scenarios. In the regions without gas network, network gas (58%), electric heaters (21%) and district heating 20% satisfy demand for heating in 2030.
    - *Flat rural.* In the regions with gas network, district heating (81%) and network gas (19%) are opted. While in the in the regions without gas network district heating (85%) and electric heaters (14%) are utilized.
- *In the coal-ban-subs scenario* (compared to coal-ban), subsidized heat supply technologies (e.g. solar space heaters, heat pumps, micro-CHP) are not widely utilized, with the exception retrofit measures (which is described below in detail). This indicates that

network gas and district heating are more economically viable substitutes to coal than subsidized heat supply technologies (solar space heaters, heat pumps, micro-CHP).

- *In the Coal-ban-subs-no-gas scenario* (compared to coal-ban-subs) there is a wide utilization of heat pumps in detached rural houses (Coal-ban-subs-no-gas), with some consumption of district heating and electricity (Fig.7c) in the regions without gas network.

a



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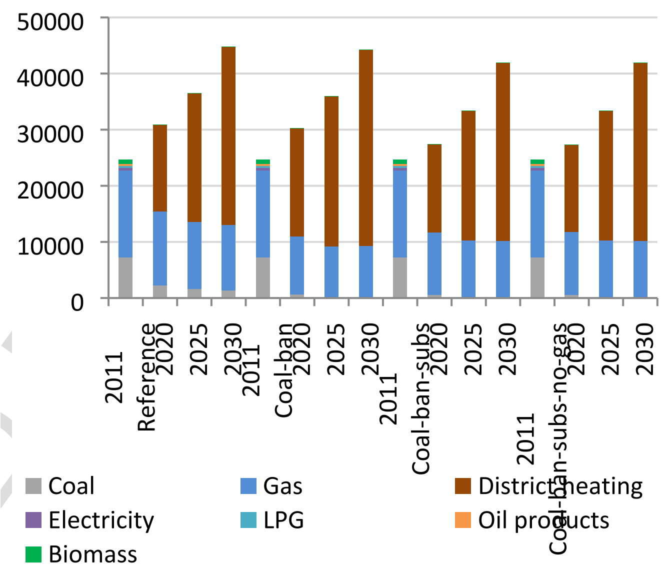

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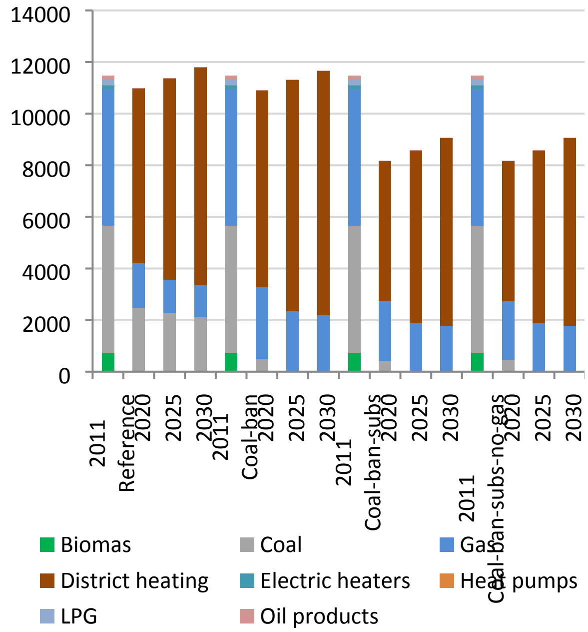


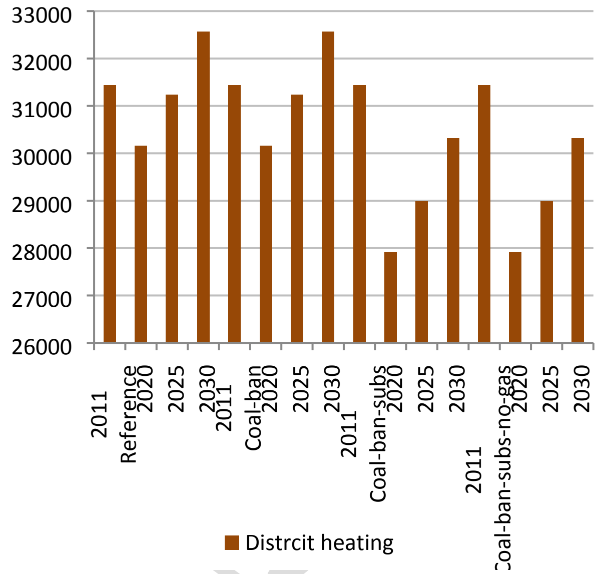
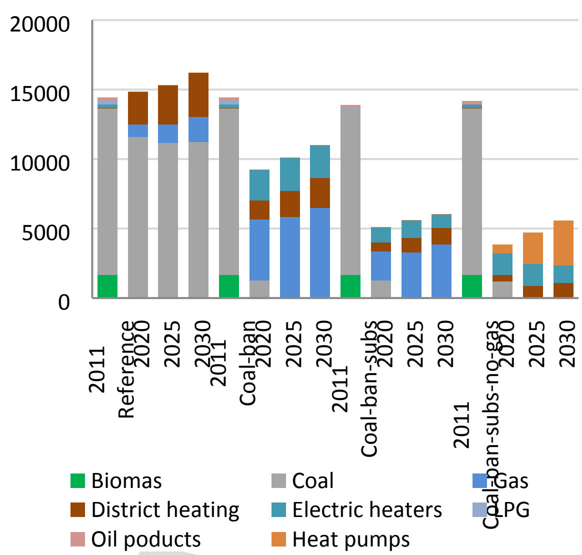
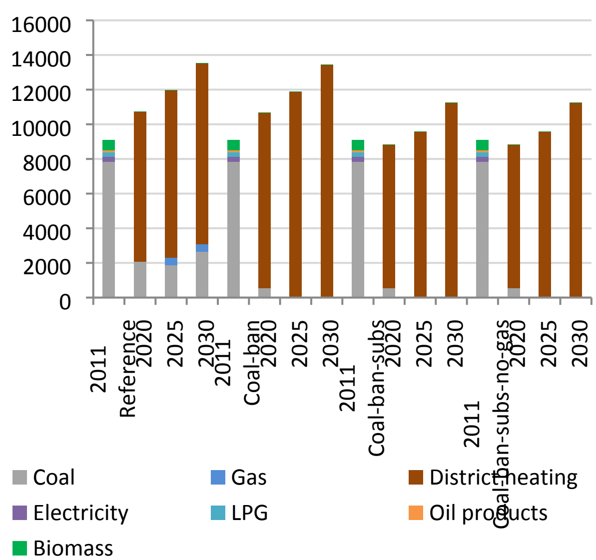


Fig. 6 - Useful energy for space heating by technology for regions with gas network availability, TJ a) detached rural, b) detached urban, c) flat rural, d) flat urban

a

b





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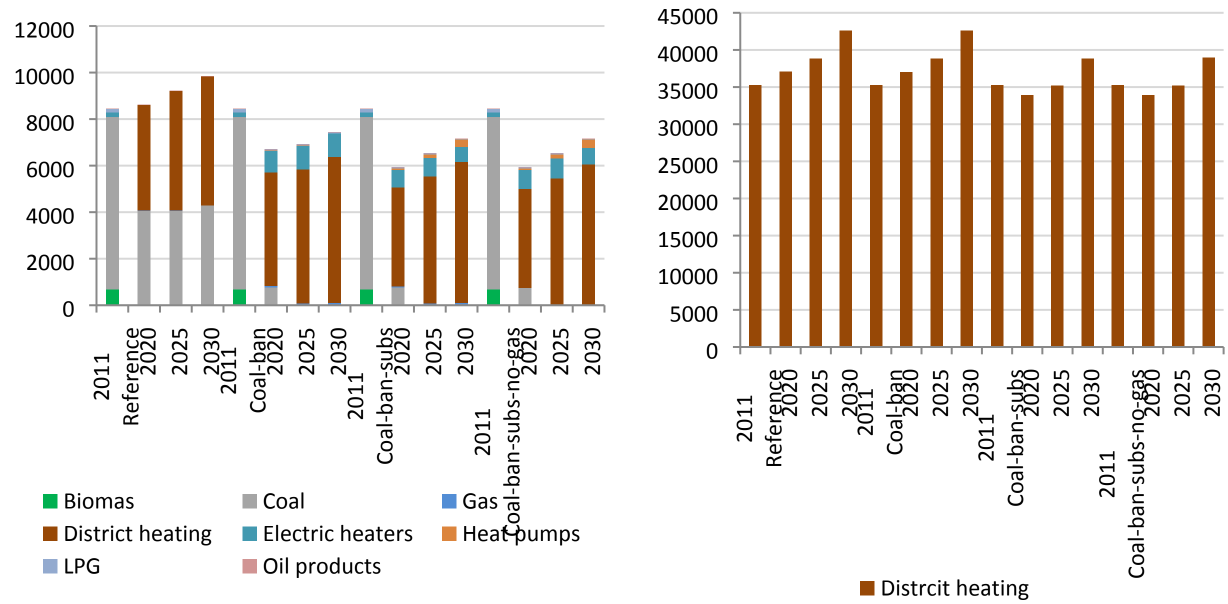

Fig. 7 - Useful energy for space heating by technology for regions without gas network availability a) detached rural, b) detached urban, c) flat rural, d) flat urban

There is a significantly higher use of retrofit measures when subsidies are offered (coal-ban-subs) compared to the case without subsidies (coal-ban) (Fig.8). There are significant differences in the share of retrofit measures between regions with gas and without gas, with notably higher penetration of retrofit measures in the locations affected by the coal ban. Detached rural houses in regions without gas network, in particular reduce useful energy demand by up to 76% when coal is banned and subsidies offered (no networked gas). Rural flats in the regions without networked gas achieve energy savings up to 39% when the subsidies are offered (Fig.8).

a b

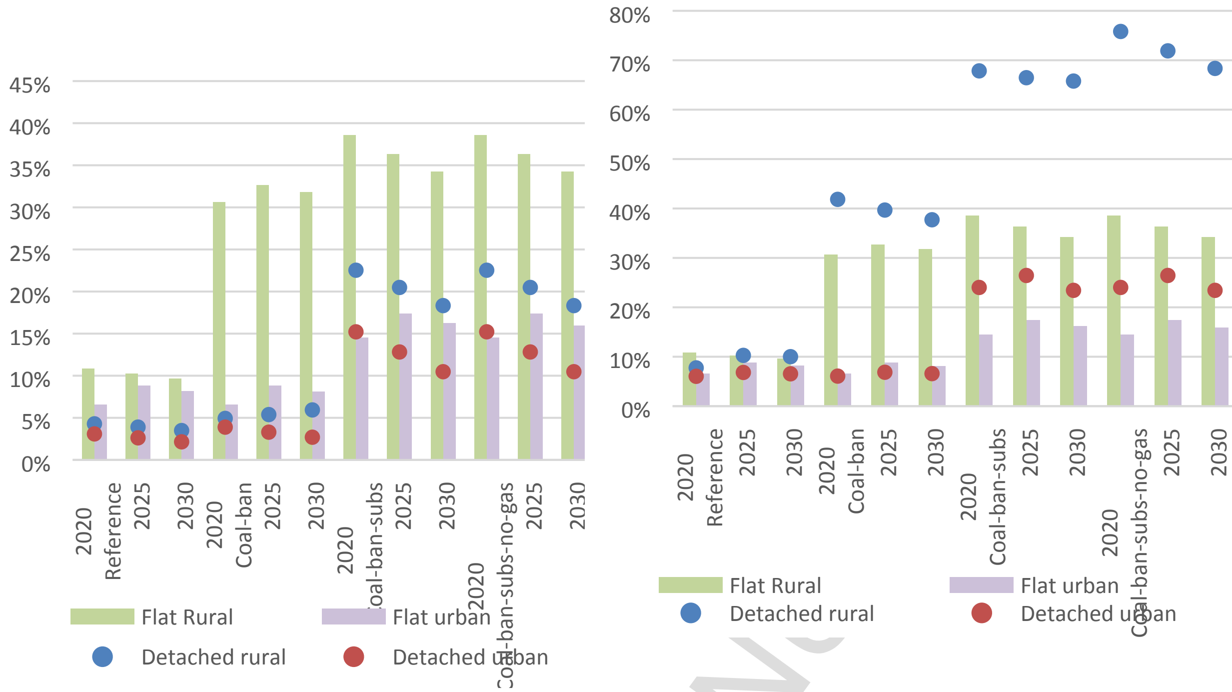

Fig. 8 – Share of useful energy for space heating reduced by retrofit measures, a) regions with gas network b) regions without gas network

3.4 Marginal price of useful energy for heating

The coal ban has only minor impacts for urban areas (due to low use of coal in urban locations), but significantly impacts on rural locations on fuel mix and price of useful energy for heating (Fig. 9). Thus, the coal ban results in an increase in the marginal price of useful energy for heating in detached rural houses by 171%, 199%, 184% by 2020, 2025, 2030, respectively in coal-ban compared to Reference (as in case of coal based Akmola region). Offering subsidies reduces the marginal price of useful energy for heating by 10%, 21%, 13%, respectively (rural detached, no gas regions) in coal-ban-subs compared to coal-ban.

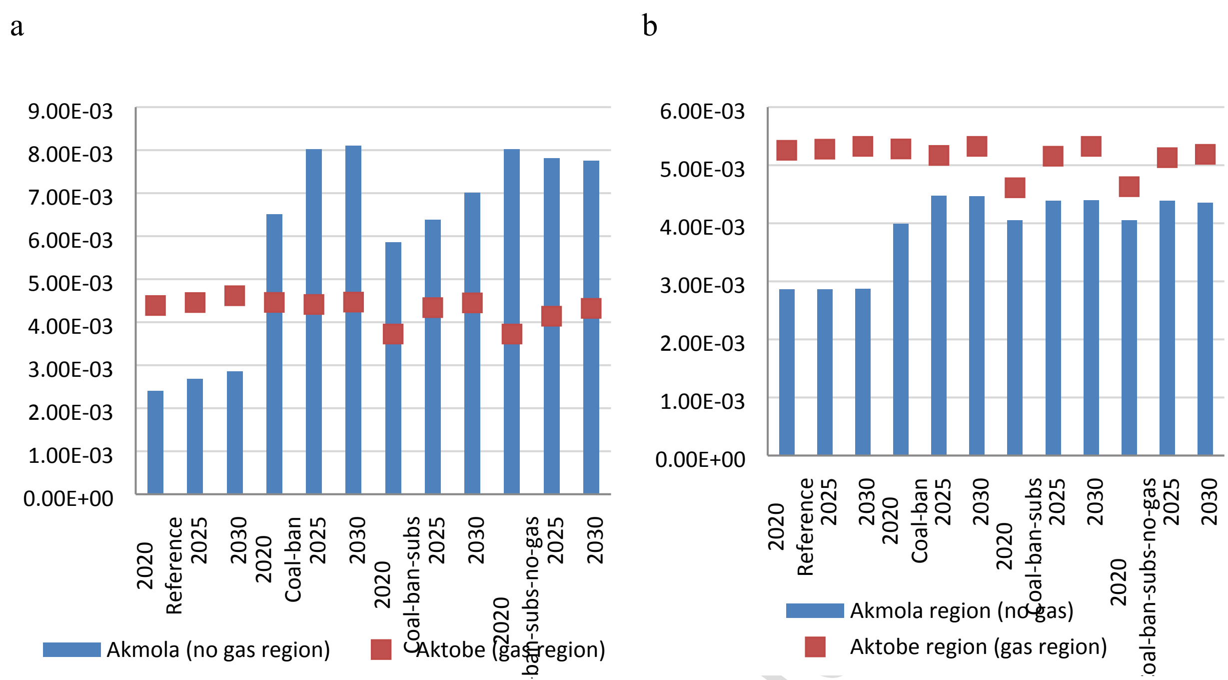

Fig. 9 - Marginal price of useful energy for heating a) detached rural, b) flat rural, USD/MJ

3.5 Emissions

In the reference scenario (optimal policy design), at national level, NO_x, $PM_{2.5}$, CO and SO_x are projected to decrease by 26%, 57%, 50% and 42% respectively, in 2030 compared to the base year level, due to reduction of coal use and some efficiency improvements. In the western regions (except for Aktobe) due to the use of networked gas there are relatively low emissions of $PM_{2.5}$, SO_x and CO in the base year and further declining trend is expected in all scenarios. In all regions (except for Atyrau), the energy transition scenarios result in a nearly 100% reduction of residential emissions of CO, $PM_{2.5}$ and SO_x in 2030 compared to base year level. While results for NO_x emissions vary from regions to region. In the western regions, NO_x emissions increase or remains stable in all scenarios due to growing demand for energy and networked gas remaining to dominate. In the regions without access to gas network, there is a 72-95% of the reduction of NO_x emissions in the energy transition scenarios.

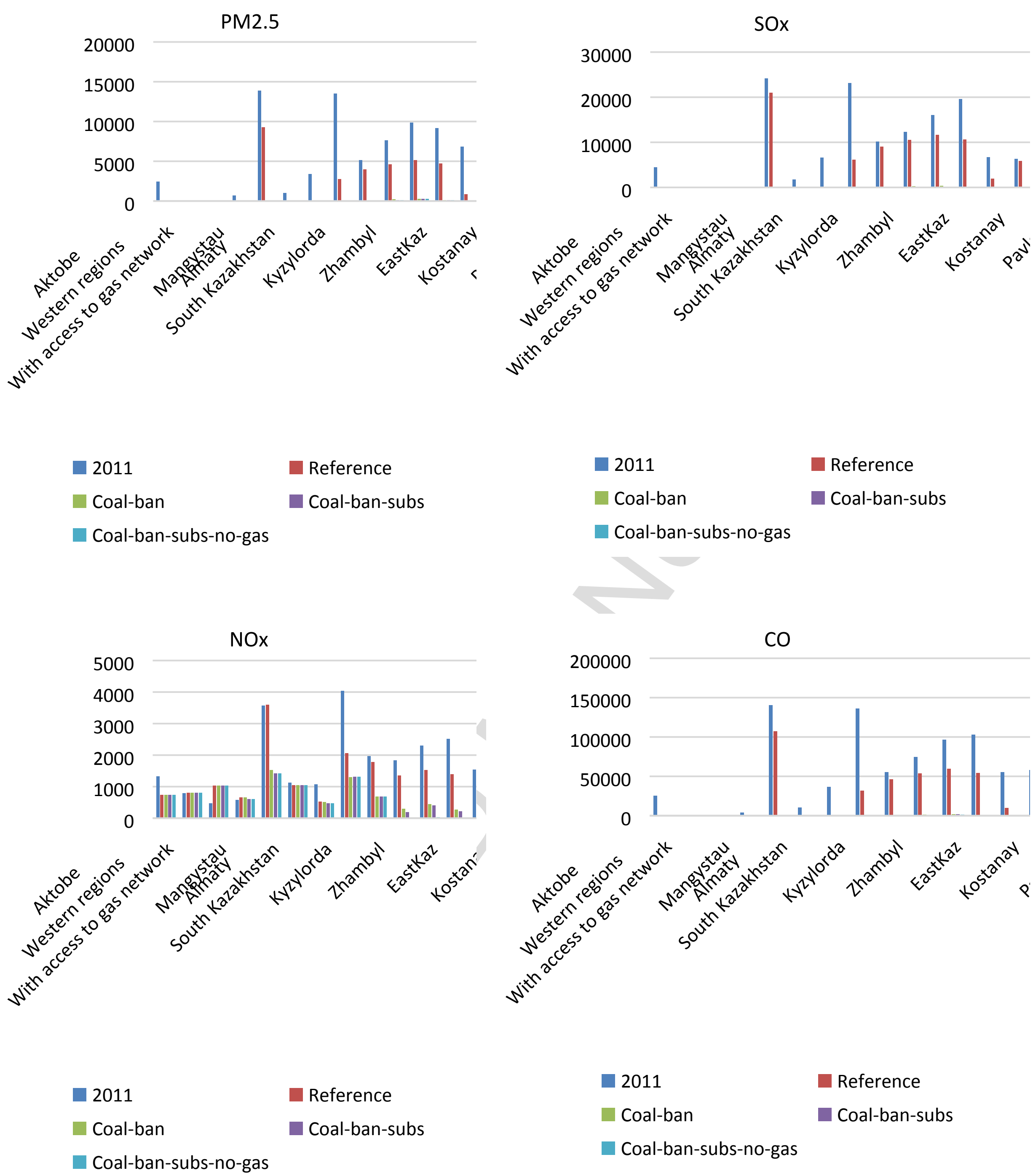

Fig. 10 - Residential sector emissions by regions and by scenarios in the base year (2011) and 2030, t

Even if additional emissions from the supply side are accounted for (power plants and heat plants), there is a considerable reduction in $PM_{2.5}$ and CO by 92% and 95% in coal-ban scenario in 2030 compared to the base year level.

Residential sector CO_2 emissions decline by 41-48% by 2030 in the energy transition scenarios (compared to the reference scenario). While total emissions of CO_2 (supply side and residential sector) decline only by 5-8% by 2030 in the energy transition scenarios compared to the Reference scenario. Here the additional electricity generation from coal offsets much of the emissions avoided in the residential sector. If pollutant controls were installed in the power plants (which is not accounted in the model), the emissions reductions could be even more significant.

Appendix G presents comparison between multiregional and monoregional model and Appendix H presents additional results on types of buildings and CO_2 emissions.

4 Discussion

4.1 Effect of model disaggregation and comparison with the previous studies

From the analysis of the heating needs it has been shown that there are substantial differences by building types (up to 2.5 times) and by regions (up to 4 times). The highly heterogeneous nature of residential heating demand across the country highlight the necessity for accounting these differences in the residential sector analysis and policies. From the model results it can be seen that the technology selection was different by building category and by region, and there was also varied effect of the specific policy assumption/scenario to the different building category and region.

It is difficult to make quantitative comparison with previous studies (models) in the literature due to different cases studies (countries), model structures (e.g. demand representation), and their applications (research question). In terms of application (research question), previous studies for UK (Dodds, 2014) and China (Shi et al, 2016) focused on residential sector decarbonization. To our knowledge none of the previous studies focused on the analysis of the specific policy interventions on households such as coal ban and clean technology subsidy.

Comparison between monoregional (PMR World Bank, 2016) and multiregional model with detailed building stock, as shown in the Appendix G, depicted that the resulting demand for heating varied considerably (by 38% in 2030) as a result of changing the methodology for its estimation. Retrofit measures plays an important role in the multiregional model with detailed building stock, while it was not selected in the monoregional model.

Gouveia et al (2012) concluded that the development of the bottom-up methodology to project detailed energy end-uses demand gives insights on the complexity between energy services and energy consumption, although limitations include the need of a substantial number of disaggregated information and the necessity of adapting or simplifying some parameters. In this study, these statements are confirmed, as analysis of the dwelling stock and assessment of the heating need reveal possible large “reduced” or “unmet” demand values. Estimated “reduced” demand values were high in some regions of Kazakhstan and it is not accounted in the official statistics and strategic planning. In this study it was assumed that in all scenarios entire “reduced” demand is satisfied. However, the model can be improved with more robust policy analysis to tackle “reduced” demand once the data on thermal comfort and occupancy from Households Survey in Kazakhstan’s buildings will be obtained.

The technology-rich and multiregional model provide additional information on:

- The dynamics of the technologies, emissions and costs by regions and by buildings types
- Policies by regions and by building types
- Impact on the supply side and synergies (due to the use of full energy system model)

The current form of the model have the following limitations:

- Absence of the data on occupancy rate and thermal comfort lead to simplified/assumed parameters
- The need for a disaggregated information on the residential sector
- Varying behavior of the households was not accounted due to the absence of data on occupancy rate and thermal comfort

4.2 Implications for policy makers

The results of this study suggest that energy efficiency potential in buildings is very high in Kazakhstan and they can serve as a key step in any of the energy transition pathways. Updating of the building insulation standards (and strictly monitoring its compliance), awareness raising campaigns, providing access to finance for building retrofits (e.g. reduced interest rates), and targeted support on building retrofit for energy-poor households have to be the key initial steps for residential sector transformation strategy.

The model results suggest that when coal is banned, networked gas is the most viable solution for rural detached houses even with alternative heat supply technologies subsidized. The most important barrier for constructing gas pipeline is its relatively high cost due to the long distances involved. Domestic gas prices in Kazakhstan are regulated at the consumer level and they are significantly lower than EU gas prices (Kazenergy, 2015). The future construction of gas pipelines largely relies on a strong political will to implement pricing reforms and/or allocation of funding from the Government.

For multiapartment buildings and urban detached houses, district heating has been chosen by the model in all scenarios. District heating is very common in Kazakhstan and 63% of housing stock in urban areas is already connected to central heating network. District heating can be environmentally clean and energy efficient when it is well managed: efficient cogeneration, clean sources of fuels (e.g. gas, biomass), and efficient distribution.

The results of this study indicate that offering subsidies/grants to coal users in rural areas for installing heat pumps with retrofits is an optimal strategy for eliminating coal consumption, if the construction of gas pipeline is delayed or cancelled. As technology penetration analysis demonstrated, 70% level of subsidy can be considered by policy makers as appropriate to support clean technologies. According to the model results, the total amount of allocated subsidies at the rate of 70% amounted for 139.9 -165.8 M USD_{2013} by 2030 and it constitutes 32% and 8% of the current state social and health care expenditures respectively (without gas availability) (Committee of Statistics of the Republic of Kazakhstan, 2016). Even though this is a considerable expenditure, it may be lower compared to the economic losses associated with indoor and outdoor air pollution, was well as excess winter deaths.

4 Conclusions

This study presents a strategic modeling framework with detailed representation of spatial, urban/rural and building type differences, and employs it to explore optimal energy system configuration of a coal-free residential sector in Kazakhstan and to quantify the impacts of subsidies for cleaner technologies. Building stock module was constructed by using a detailed bottom-up analysis of the stock of buildings. The methodology for determining heat demand was improved in the model by assigning surface area of the dwelling stock as a driver of heat demand. The specific benefits of this demand representation include representation of costs and energy savings of building retrofit measures by building type as well as representation of "reduced" heat demand in the model. The disaggregation enabled to provide residential sector energy transition pathway by regions and by building types. These amendments had an impact on total residential energy consumption as well as fuel and technology choice.

The results demonstrated supply side energy infrastructure plays an important role in the coal-free residential sector pathways. Constructing infrastructure for providing district heating and networked gas coupled with significant energy efficiency measures are the least-cost solutions for coal-free heating in Kazakhstan. Retrofitting measures are used by all building types, but they play a crucial role in reducing heating demand in coal dependent buildings, when a coal ban is introduced. For flats, combining district heating with energy efficiency is almost the single optimal solution. Without a gas pipeline option to non-gas supplied regions, ground-source heat pumps satisfy most of the demand for heating in rural locations coupled with extensive building retrofits. The coal ban alone may have a significant impact on energy affordability (as there was significant impact on marginal price for heating) and it should be accompanied with subsidies for retrofits and heat pumps. Subsidies for clean technologies should be primarily targeted to rural population relying on coal, while retrofit measures can be offered for all building types. Coal ban in the residential sector almost completely eliminates emissions of $PM_{2.5}$ and CO in the sector.

The results can serve as a basis for National/regional strategies for residential sector policies. The approaches for model improvement and addressing data limitations can be replicated to other countries/cases.

The key limitations of this study are that the occupancy rate and indoor air temperature parameters had to be estimated and simplified, due to the lack of surveys and field data. Future studies should concentrate on households survey of these parameters and behavioral issues, as well as epidemiological studies quantifying health impacts. Future research should be conducted to reduce costs and increase efficiency of heating technology options for remote cold climate regions. Uncertainty to multiple variables simultaneously also needs to be modelled.

Acknowledgements

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Appendix A. Energy Balance and Household Enegy consumption

The energy balances provided by the Committee of Statistics of the Republic of Kazakhstan (CSRK) served as a main source of data for the model. The format of energy balances of Kazakhstan, published by the CSRK does not comply with commonly used international formats (e.g. IEA (International Energy Agency) and Eurostat) and can not be directly employed for modeling purposes (Kerimray et al, 2017b). In this regard, for modelling purposes in this study energy balances provided by CSRK were reclassified according to the IEA Energy Statistics Manual. Improved versions of the Energy Balances for Kazakhstan were compiled and cross-checked with additional data provided by the Kazakhstan Electricity Grid Operating Company (KEGOC), the Ministry of Energy of the Republic of Kazakhstan (ME RK), the Information-Analytical Centre of Oil and Gas (IACOG) and the Committee of Statistics of the Republic of Kazakhstan (CSRK), as part of this study. Detailed methodology for compilation of improved energy balances were described by Kerimray et al (2017b). The main principle in an energy balances compilation was to “close” a balance between supply and total consumption by eliminating statistical differences. Sum of all regional balances gives national energy balances for each sector and fuel. Sum of all regional imports and exports for each commodity is equal to avoid double counting or underreporting of fuels.

Residential energy consumption in the Energy Balances was obtained based on the results of two surveys on household living conditions: the ‘Quarterly Budget Survey of Households’ and the ‘Annual Household Survey’ which cover 12,000 households in Kazakhstan (Kerimray et al. 2017a). These surveys were both administered by the Committee of Statistics of the Republic of Kazakhstan. Households were selected by random sampling based on data from a Population

Census. The households selected were considered to be representative at both the national and regional level. The surveys covered all 16 administrative regions in Kazakhstan and the number of households varied between 0.1 and 0.5% of the total in each region. Fifty-two per cent of the households surveyed were urban, and the remaining 48% were rural. The survey results show that 40% of the households surveyed use coal and 25% use firewood. Coal and biomass consumptions in the residential sector were thus estimated from data for coal and biomass expenditure (from the Household Survey) and prices.

Appendix B - Assessment of heating need by building type

The heating need calculation methodology follows ISO 13790 "Thermal performance of buildings and building components". The energy need for space heating is calculated according to:

$$Q_{H,n} = Q_{H,ls} - \eta_{H,gn} \cdot Q_{H,gn} \qquad \text{(B.1)}$$

Where $Q_{H,n}$ is the building energy need for heating, in kWh per year; $Q_{H,ls}$ is the total heat transfer for the heating mode, in kWh per year; $Q_{H,gn}$ are the total heat gains for the heating mode, in kWh per year; $\eta_{H,gn}$ is the dimensionless gain utilisation factor. The total heat transfer, Q_L, of the building zone for a given calculation period, is given by:

$$Q_{ls} = Q_{tr} + Q_{ve} \qquad \text{(B.2)}$$

Q_{ls} is the total heat transfer, in kWh;

Q_{tr} is the total heat transfer by transmission, in kWh;

Q_{ve} is the total heat transfer by ventilation, in kWh

Input data used for heating need assessment is presented in Table B.1. Reference values for Kazakhstan ENSI EAB (Software for building energy auditors), building energy audit reports and assumptions were used to complete Table B.1.

Table B.1. Summary of input data for the assessment of energy need for heating

Parameter	Unit of measurement	Value
Total solar gain, g	-	0.5

Infiltration	1/h	0.5
Indoor temperature θI,H	˚C	21
Heating hours	h/d	24
Heat capacity C'm	Wh/m^2K	72
Lighting operating period	h/week	84
Average power of lighting	W/m^2	3.5
Various exploitable equipment operating period	h/week	72
Various exploitable equipment average power	W/m^2	2
Metabolic heat from men	W/person	93
Metabolic heat from women	W/person	79
Metabolic heat from kids	W/person	70
Time present indoors for men	h/d	12
Time present indoors for women	h/d	24
Time present indoors for kids	h/d	24

Appendix C – Reduced demand and occupancy

The highest values of "reduced" demand were in coal-based regions: North Kazakhstan (32% of theoretical heating need), Akmola (25%) and East Kazakhstan (21%).

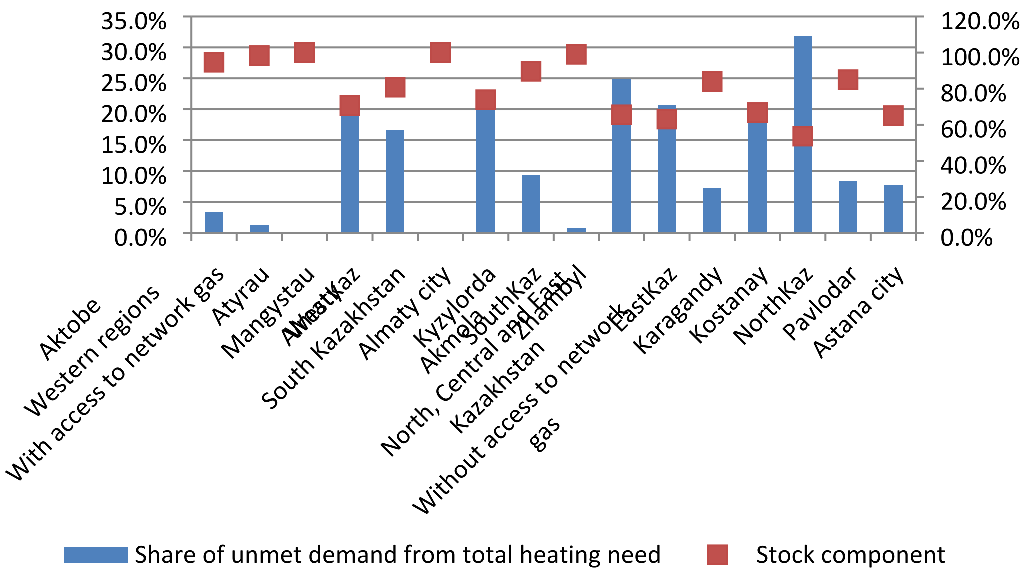


Fig. C.1 – Share of reduced demand to theoretical heating need of the region and assumed stock component.

The model run without constraint to satisfy "reduced" demand resulted in 32920 TJ of lower energy consumption in the residential sector (Reference scenario) in 2030 (compared to the case with "reduced" demand satisfied) (Fig.C.2). This is 7% of total residential consumption in Reference (with reduced demand satisfied).

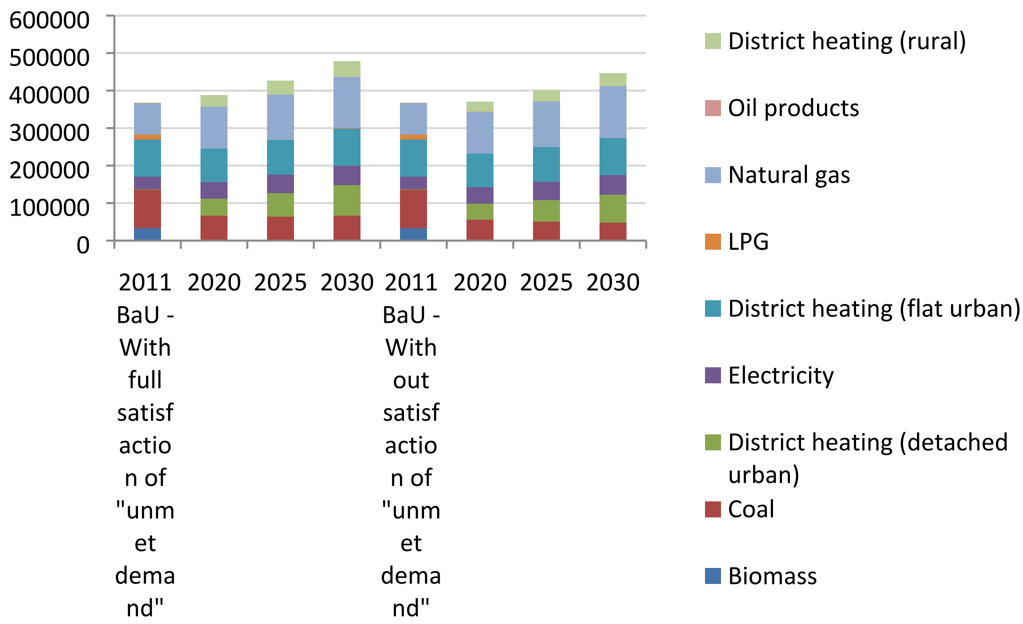


Fig.C.2 – Reference results with and without reduced demand satisfaction

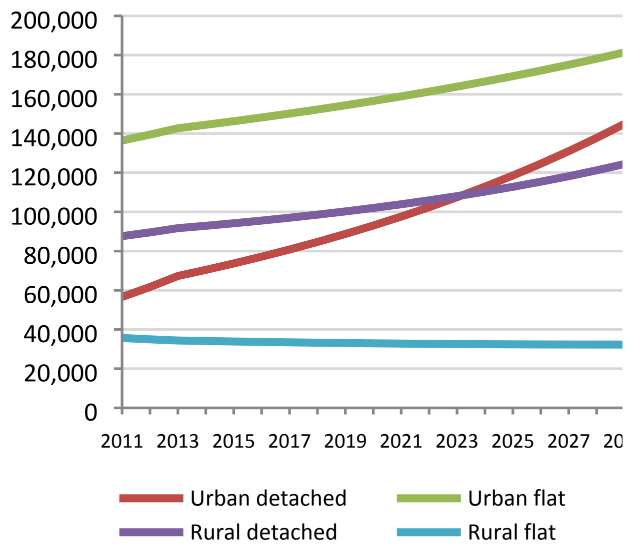
Appendix D – Demand drivers

The total amount of heated area served, which is a driver of the demand for space heating, water heating and cooking is presented in Figure D.1. The total annual increase in living space corresponds with the parameters of the State Program "Affordable Housing - 2020": about 7-8 M m^2 of new areas annually. Historically, living surface area per capita has grown by 20% from 17.9 m^2 in 2007 to 21.4 m^2 in 2016. Expected living space area per capita is 24 m^2 in 2030.

In the estimates of future area of the dwelling stock by 2030, it is assumed that the current ratio between the growth rates of various types of housing stock (by regions, urban/rural, detached/flat) is maintained. This ratio between the growth rates of various types of housing stock (by regions, urban/rural, detached/flat) is obtained on the basis of historical data for 2008-2015.

The fastest growth rates, based on these estimates, are observed in urban detached houses, with an almost 3-fold increase by 2030, compared to 2011. The total area of the housing stock is projected to increase by 1.5 times by 2030 compared to the level of 2011.

a



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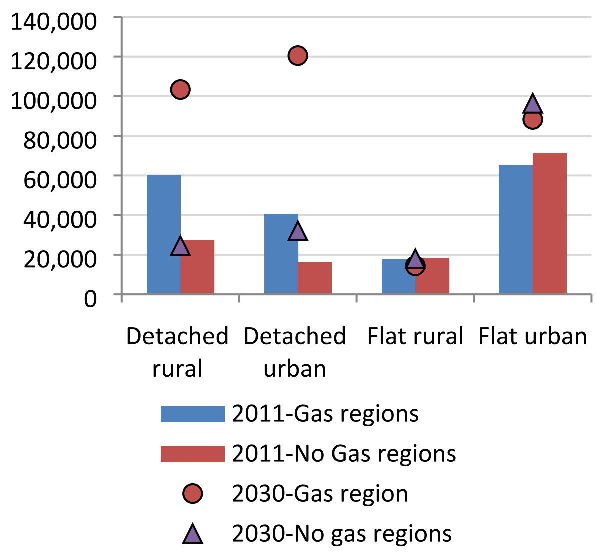


Fig. D.1. Projected total area of dwelling stock a) by type and b) by regions and by type, thousand m^2

Appendix E - New technology database

Technology database was inherited from the national (single region) TIMES-Kazakhstan model: the latest updated version by Nazarbayev University Research and Innovation System (Kazakhstan) under the Project funded by Partnership for Market Readiness (2015-2016). There are 59 technologies described for electricity and heat generation (e.g. coal supercritical power plant, IGCC plant, integrated gasification combined cycle plant, gas steam plant, biomass and municipal solid waste plant, wind onshore, wind offshore, nuclear plant, among others). There are 48 and 71 technology options in the residential and commercial, and public sectors, respectively (e.g. coal stove, gas water heater, washing machine, incandescent bulb, heat pump and others). In the transport sector, there are 279 technology options (e.g. LPG, diesel, gasoline, ethanol, fuel cell, light vehicles/buses/light trucks/heavy trucks/, etc.) and in the industry sector there are 38 technology options (standard pulp and paper, improved pulp and paper and others.).

The following technology databases were used for describing new technologies:

- European Commission Joint Research Centre (2014). Energy Technology Reference Indicator projections for 2010-2050. https://setis.ec.europa.eu/system/files/ETRI_2014.pdf
- IEA-ETSAP (2010-2014). E-TechDS – Energy Technology Data Source https://iea-etsap.org/index.php/energy-technology-data/energy-supply-technologies-data
- World Energy Outlook (2014). Energy efficiency in end-uses. http://www.worldenergyoutlook.org/weomodel/investmentcosts/ (cooking, lighting, appliances)

- UK Energy Research Centre University College London (2011). TIAM-UCL Global Model Documentation https://www.ucl.ac.uk/energy-models/models/tiam-ucl/tiam-ucl-manual

“Passive” houses were represented in the model as an alternative to new houses (with standard heating need), with their own costs and heating need (Table E).

Table E.1. Parameters of passive house represented in the model

Parameter	Passive house
Heating demand	22.4 kWh/m^2 per annum (Schnieders et al., 2015)
Cost	15% more than conventional house (upper range was taken due to low market penetration in Kazakhstan) (Galvin, 2014)

Appendix F – Gas infrastructure

The capital cost for new gas pipeline infrastructure was estimated using capital costs for recently constructed gas pipeline Beineu-Bozoi-Shymkent (Southern Kazakhstan) and it was estimated at 7M USD/(TJ*km), which is higher than the cost of Tobol-Kokshetau-Astana (Central Kazakhstan) (6M USD/(TJ*km)). Potential gasification routes described in the model include all possible routes ever discussed by the Government to bring gas to non-connected regions in Central Kazakhstan (particularly capital city of Astana):

- "Saryarka" pipeline starting from south of Kazakhstan (Kyzylorda region)
- "Tobol-Kokshetau Astana" pipeline starting in the northern Kazakhstan (Kostanay region)
- "Karachaganak-Astana" pipeline starting in the North West of Kazakhstan (West Kazakhstan region)

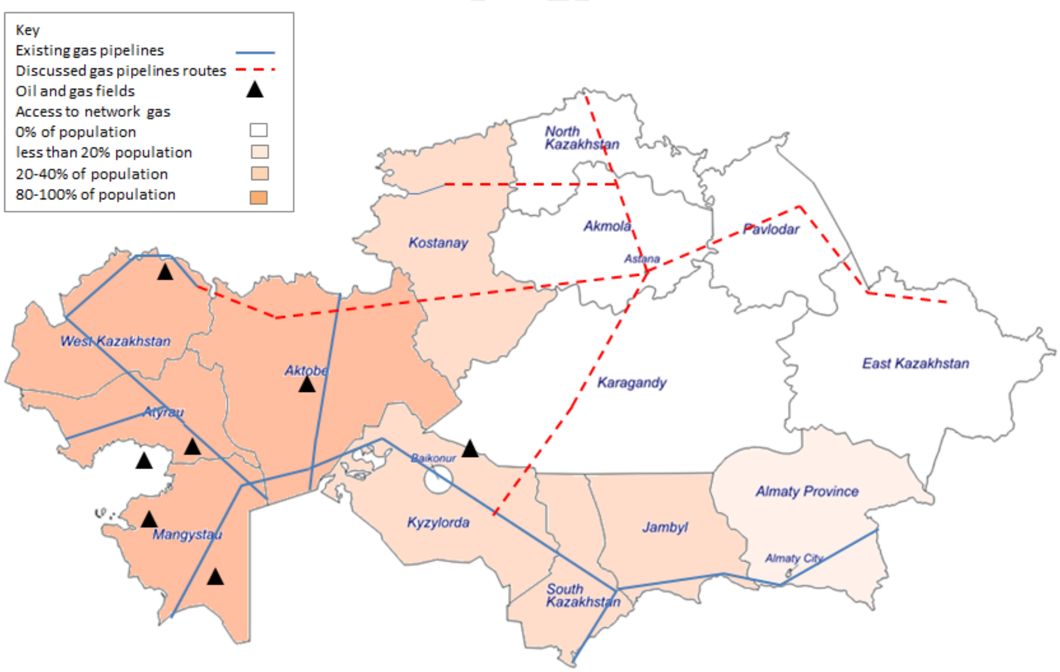


Figure F.1 - Existing gas pipelines and possible routes for gasification

To cover all regions of Kazakhstan, possibility for investing in the extension of gas pipeline routes (starting from the abovementioned pipelines) further to the North Kazakhstan region, East Kazakhstan, Akmola region and Karaganda region were also described.

Appendix G – Comparison between multiregional and monoregional model

In order to assess the deeper insight gained through the improved model, the projections of TIMES-Kazakhstan single-region model, further named as “monoregional” model, were compared to the refined or “multiregional” model. The monoregional model was updated in 2015-2016 to access impacts of different mitigation policies under the project funded by the World Bank Partnership for Market Readiness (PMR Kazakhstan, 2016). There is no disaggregation to urban/rural and flat/multiapartment buildings in the monoregional model and the driver of the demand for residential heating is the population growth. In the aggregated model, “reduced” demand was estimated using simplified approach by comparing with the national average “heating need” estimate from the State Program “Energy Saving -2020”. Scenario with coal-ban on the residential sector was compared between two models.

The average annual growth rate of the demand for heating during the period 2011-2030 is 3% in the monoregional model and 6% in the multiregional model. This difference occurs due to change of the drivers for heating demand: population (with corresponding correlation factor) in the monoregional model and dwelling stock in the multiregional model.

Total residential energy consumption in 2030 is 9% higher in the multiregional model than in the monoregional model. The fuel mix is considerably different. As an example, consumption of district heating is 70% higher in the multiregional model compared to the monoregional model. While natural gas consumption is 11% lower in the multiregional model compared to the monoregional model. Insulation measures are not chosen in the monoregional model.

Appendix H – Additional model results

1.Dwelling type

In 2030, new buildings (including passive) account for 46% of the total housing stock. Passive houses account for up to 3% of new buildings and they are mostly used in Coal-ban scenario (without subsidies scenario) (Fig.H.1).

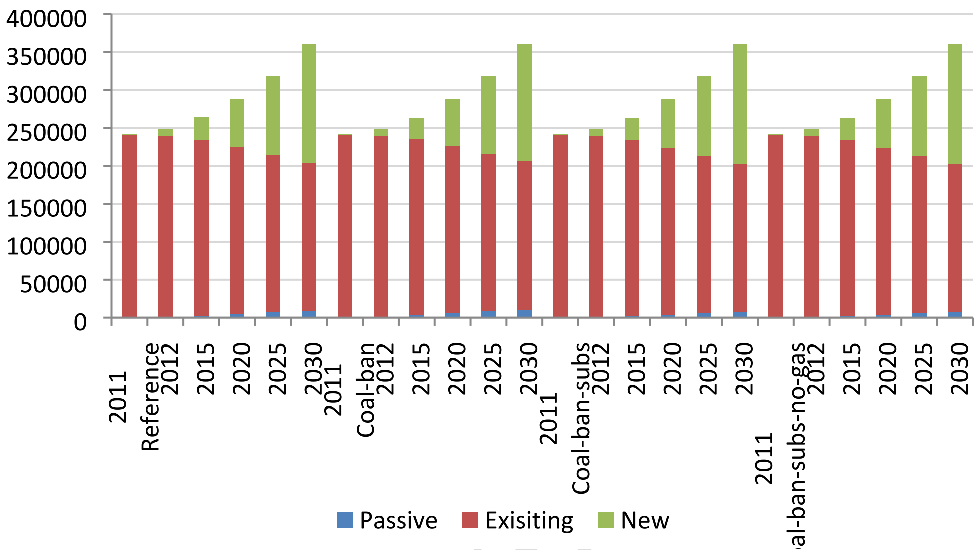
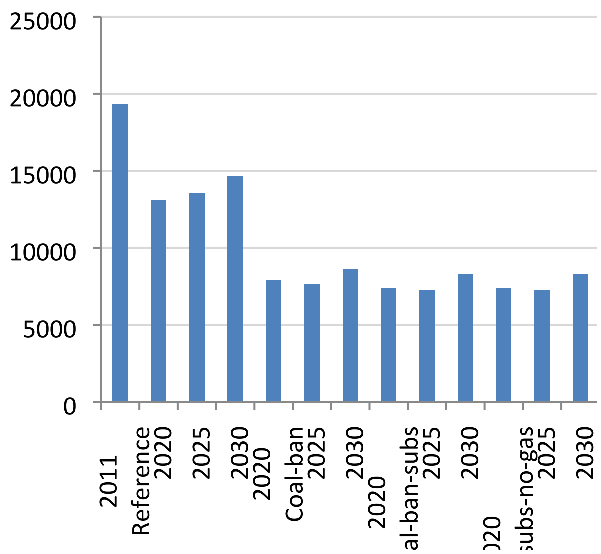


Fig. H.1 Dwelling stock, thousand m^2

2. CO_2 emissions

a



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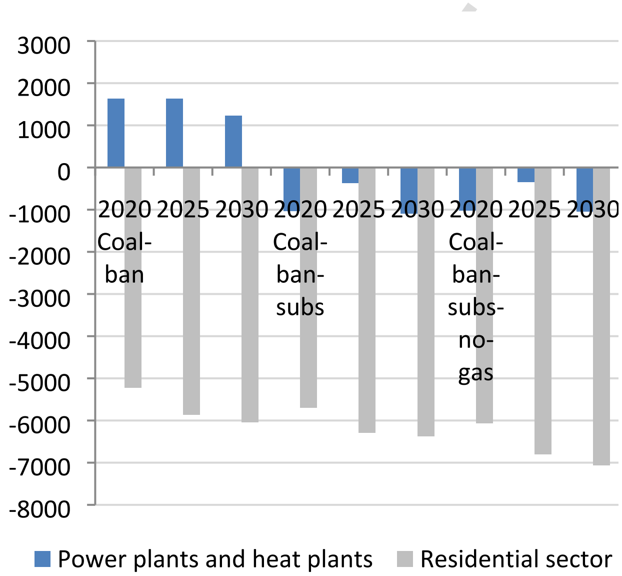

Fig.H.2 –a) CO_2 emissions from residential sector, kt b) Difference in CO_2 emissions between alternative scenarios and Reference for residential sector and power plants, kt